THE OSAR GRAVELS OF THE COAST OF MAINE.[1]

In the interior of Maine we find the long osars interrupted near the tops of transverse hills crossed by the glacial rivers, and still more interrupted on steep southern slopes. In such situations it is evident that the velocities of the osar rivers would be greater than the average, with the result that the rivers swept their channels clear of sediments. The conditions were those of transportation by the glacial rivers rather than deposition.

If we follow the osars southward toward the ocean we find at about the average distance of thirty miles from the shore that the osars begin to be interrupted in a different manner from that in the interior. Gaps begin to appear in the ridges in level ground where the land slopes could not cause an accelerated motion of the glacial rivers. Indeed, the gravels more often appear on the tops of low hills than in the lower grounds. Going southward the sizes of the ridges become on the average smaller, their materials rather coarser, the intervals longer, and finally near the northern ends of the bays or fjords of the coast they disappear. If they continue farther southward or into the sea, it is in masses that are so small as to be covered out of sight by the marine beds. The coastal towns are usually covered by clays, and road gravel is often in great demand. The vigilance of town officers has often detected beneath the marine clays small mounds of gravel that form the southern ends of gravel systems. To the south we reach a region where no gravels have been found. When we find an osar system graduating into mounds so small that not even the selectmen of a Maine town can find water-washed road gravel, we may be sure that our osar has come practically to an end. I have examined the charts of the Coast

[1] Condensation of chapters of a report on the Glacial Gravels of Maine, written for the U. S. Geological Survey.

Survey showing the sea bottom for a few miles off the coast. If there were any broad gravel hills 100 to 150 feet high, such as are found thirty miles north from the bays, they ought to be shown, and I do not find them. The charts often report gravelly bottom but it is uncertain whether this is till or glacial gravel. I find no evidence that these soundings showing gravel are connected with ridges of any considerable size. While then it is as yet impossible to know the geological significance of the gravel reported on the sea floor, yet in most cases the gravels end so evidently north of the shore that the interpretation is distinctly favored that none of the gravel systems reach far beneath the sea. No osar gravels have I been able to find on the islands situated south of the apparent ends of the gravel systems.

There are other significant peculiarities of the coastal gravels than those to be named in this paper, and many collateral or alternative questions and hypotheses had to be worked out. For the present we confine our attention to the three following characteristics :

1. The decrease in the average size of the glacial gravel masses as we go toward the coast till they often become cones not more than twenty or thirty feet in diameter and four or five feet high. In general, the marine clays are twenty feet or more in depth and would easily cover out of sight masses smaller than those above named.

2. The increasing discontinuity of the osar systems, the gaps between the successive ridges, massive mounds or plains, lenticular hills, domes, cones, and mounds increasing from a few rods up to two or three miles.

3. The practical ending of the osar gravels near the north ends of the fjords (fjord line). It is not meant to assert that there are absolutely no osar mounds beneath the sea or on the land south of the discovered gravels. But if any exist they are hidden by the marine beds, and are so insignificant in size as compared to the osar gravels found a few miles farther north that for all practical purposes we may assume that they end. If the osar mounds go on decreasing as fast southward as they do

within the last few miles of their traceable courses, they certainly must entirely disappear within three to five miles of their apparent endings. We omit here the overwash gravels that were deposited in front of the ice beneath the present ocean.

It is to be noted that these gravels are in lines or systems, and often toward the north pass into continuous osars. They are regarded as having been deposited by a single glacial river, that is, all that are classed as a single system. The intervals between the separated gravel masses are not due to erosion of a once continuous body. But the problem relates to the reasons why a single glacial river deposited sediments at intervals here and there within its channel.

In placing the problem before us, we have to consider the extent of the region in question. The above-named characteristics are associated with each other along two hundred miles of coast. Every few miles throughout this district we come to places where a glacial river has left its sediments. All these gravel systems exhibit the first two of the above named characteristics, and all but four or five, the last. Three osars end at the shore but near the north end of Penobscot bay several miles north of the general fjord line. Two others, perhaps the largest systems in the state, come down to the shore and the soundings seem to support the conclusion that they extend for a short distance under the sea. Horizontally, these changes mostly take place within a belt not far from thirty miles in breadth; vertically in most cases between sea level and the two hundred feet contour. The last named, the ending of the gravels, occurs between contours hardly fifty feet apart.

It is granted that the sea in late glacial time stood along the outer coast line, a little more than two hundred feet above its present level. In the interior its elevation was more than twice this height. All the beaches along the outer coast, whose height I have measured, have nearly the same elevation. In other words, the surface of the sea in late glacial time was substantially parallel to its present surface in the direction of the coast, though at a higher level.

In the coastal region we find numerous marine glacial deltas deposited in front of the ice by glacial rivers that flowed into the sea, but we do not find such frontal or overwash sediments as naturally form in front of glaciers terminating above sea level. These and other facts prove that the ice had not all melted over the coastal region before the advance of the sea. The subsidence of the land (apparent advance of the sea) either preceded the retreat of the ice over the coastal region or accompanied it in such a manner that all the land free from ice was covered by the sea as fast as the ice melted, up to the time when the sea had advanced northward to the highest beach. That is, up to this time, all the subglacial streams poured into the sea at the ice front and not on land above the sea. It follows that the causes of the ending of the osar systems north of the shore not only acted parallel to the present and former surface of the sea, but also in a region where the basal ice was bathed in sea water.

The presence of deep glacial pot-holes in considerable numbers near the coast proves the existence of subglacial streams in that region. Since there are no glacial gravels near these pot-holes, we have proof that there were rapid subglacial streams that left no gravels. Evidently their velocities were such that they transported all their sediments beyond our field (out into the region now under the sea). For years my conclusion has been that the osar rivers of the coastal region of Maine were all subglacial. Assuming the subglacial streams, the problem now resolves itself into this: How happened it that as the subglacial rivers approached the coast, they all found themselves able to sweep their channels free from sediments at nearly the same elevation?

Without here pausing to consider the genesis of the subglacial tunnels, we confine ourselves to the question, how are the tunnels enlarged? Two physical agencies do most of the work. First, mechanical erosion; second, melting of the ice walls by surface waters. In the case of ordinary mountain glaciers there is usually considerable land on the mountains that is bare of ice, and thus water warmed on the land passes beneath the ice and

helps to enlarge the subglacial or englacial channels. But, in the case of ice sheets covering all the land, the only heat available for enlarging the tunnels (omitting the small amount of basal heat) is the heat absorbed by surface waters and carried by them beneath the ice. It is known that the waters of surface melting often collect in superficial brooks and torrents of considerable size. The absorption of radiant energy from the sunlight is instantaneous, or at least much more rapid than the conduction of this energy as molecular heat from the water to the ice with which it is in contact. Under sunlight all surface waters become warmed a little above 32°, and, as they plunge beneath the ice, they give up their surplus heat to help melt the walls of the subglacial channels. This, I infer, is the most efficient of all the agencies that help to enlarge the subglacial tunnels. Enlargement of the subglacial tunnels is not uniform. Thus, where a surface stream pours beneath the ice and brings a fresh supply of heat into the tunnel, there would be more rapid enlargement than elsewhere. For various reasons, not necessary to be discussed here, the enlargement of the tunnels proceeds unequally.

Given a tunnel gradually enlarging till sedimentation begins, this sedimentation will commence at the most favorable places, as at the local enlargements, or at an obstruction. If, now, the size of the tunnel, or rather the ratio between the tunnel capacity and amount of water increase, sedimentation will take place at more frequent intervals, and if the tunnel becomes large and rather uniform in size, the sediments will form a continuous ridge.

Various causes can be adduced why a glacial stream should deposit a diminishing quantity of sediment, but the controlling cause and almost the only one admissible under the peculiar local circumstances is the following: We grant that as we go southward toward the distal extremity of the glacier the supply of drainage water will increase, as in all drainage systems. But all these surface waters take with them heat as they pass beneath the ice to help enlarge the tunnels. Thus, as it were, each

region of the glacier furnishes the heat to enlarge the tunnels within its own limits. This is the natural career of ordinary ice sheets above the sea.

An important law of the enlargement of subglacial tunnels depends on the velocity of ice movement. Subterranean waters, as those of the limestone caves, go on enlarging their channels from age to age, because they act continuously on the same body of rock. But the subglacial tunnel cannot become thus enlarged, because of the constant renewal of the ice. Other things being equal, the enlargement of the subglacial tunnels is directly proportional to the time during which it is being enlarged, and inversely as the rate of ice flow. Obviously, when the flow is rapid the tunnel never becomes very much enlarged, for before this can happen the ice at any given part of the channel is pushed on to the distal extremity and disappears by melting or by berg discharge.

The details, here omitted, prove there was probably a small acceleration of the rate of ice flow as the coast of Maine was approached, hence the rate of enlargement of the ice channels would not increase so rapidly as the supply of water of local melting. But the surface of that region is much diversified with hills and valleys. The rate of ice flow would be most rapid in the deeper north and south valleys, and would be retarded in the lee of the higher transverse hills, of which there are several long systems. If differences in the rate of ice flow were the only cause of different rates of ice channel enlargement, then we ought, on such an uneven coast, to find evidence of the fact in the distribution of the gravels. Examination shows that this was a real cause of varying rates of enlargement, but it was a minor cause. This cause alone could not have enabled all the subglacial rivers to clear their tunnels of sediments at the same or nearly the same horizontal line. It would have acted at various levels, according to the conditions for rapid ice supply from the north.

We have seen that the ice in late glacial time flowed into the sea in the coastal region of Maine. It remains for us to inquire

what is the effect of the flowing of a glacier down into a body of water upon the enlargement of the subglacial tunnels. In such a case the tunnels and all crevasses opening into them are permanently filled with water up to the level of the surface of this body of water. But it is by the crevasses that the waters of local melting get down into the subglacial tunnel. The permanent water in the crevasses is at the temperature of 32°. As the waters of surface melting in the region whose basal ice is submerged in the sea or other body of water pour into the crevasses they cannot at once fall to the ground and enter the tunnels, but they fall into the water in the crevasses that already fills them to the level of the permanent body of water. The large streams find their way pretty directly into the tunnels, but all the smaller streams and trickles become so mixed with the cold waters in the crevasses that their heat, instead of being consumed in enlarging the tunnels, is largely expended in melting the ice walls of the crevasses above the level of the tops of the roofs of the tunnels.

Thus the flowing of a glacier down into the sea interferes with the natural transfer of heat beneath the ice whereby the tunnels are enlarged in large part. But the supply of surface waters is the same over the area whose base is submerged as elsewhere. The conclusion follows, that as we go toward the distal extremity of a glacier that flows into a body of water, the supply of drainage waters would be increased more rapidly than the tunnel capacity. This would result in increased velocity of the rivers, with a corresponding increase in power of transportation. In other words, they would do just as the osar rivers of Maine did as they approached the coast—would deposit sediments at longer and longer intervals, and in smaller quantities, and finally would sweep their tunnels free from all sediments.

Now it is certain and inevitable that the submergence of the basal ice should restrict the enlargement of the subglacial tunnels, yet it is an open question whether this was sufficient to account for the peculiar development of the coastal gravels.

We have seen that these changes take place within a belt not

far from thirty miles wide. Without assuming any definite rate or rates of ice movement we can at least all agree that it would take many years for the ice to advance such a distance. An obstruction to the natural transfer of heat beneath the ice, and consequent enlargement of the tunnels, though it might be slow in its action, would, after a term of years, have a cumulative effect on the development of the tunnels, at least in cases where the subglacial rivers flowed in channels parallel with the ice flow.

We have seen that the three features of the coastal gravels above stated are associated together over a wide area, and would appear to have a common origin. Glacial rivers of different lengths, from five up to more than one hundred miles, all show the same development. At almost the same elevation they all were able to sweep their tunnels clear of sediments. We must seek for some cause capable of acting along two hundred miles of coast in lines approximately parallel to the surface of the sea. What but the sea itself could do this under so many varying topographical and glacial conditions?

Rightly interpreted, it would appear that the termination of the gravel systems north of the shore line is itself a proof of the former elevation of the sea. We may leave it as an open question how far the sea acted in other ways — such as by diminishing the effective "head" of the subglacial streams, etc., but that the sea was chiefly responsible for the peculiar development of the coastal gravels, I am persuaded, is the best interpretation of the facts. And of all the ways in which the sea or other body of water that submerges the base of a glacier affects the subglacial streams and their tunnels, I have been able to discover none so potent as that which is above described, whereby the enlargement of the tunnels is obstructed.

Where subglacial rivers flowed up and over transverse hills, as they often did in Maine, there would be a body of slack water in the tunnels, like a sewer trap, on the north sides of the hills. Some of these bodies of slack water or dams on the north sides of hills were from five to ten or fifteen miles long, and in one

extreme case about twenty miles. The ice would be so long passing over such distances that we could expect that the basal water would restrict the enlargement of the tunnels sufficiently to show a characteristic development of the gravels, such as narrowness of the osars or gaps without gravels. While in such situations I nowhere find so extreme a development as in the coastal region, yet there are numerous facts that are best interpreted by the hypothesis that the basal waters of the slack water dams in the subglacial tunnels did somewhat obstruct the enlargement of the tunnels; and thus far I have found none inconsistent with that hypothesis.

The critical reader will have noted that the belt of transition of the coastal gravels of Maine is approximately parallel to the ice front at one stage of the retreat of the ice. It is also somewhat parallel to the southern margin of the *névé*. It has been necessary to consider whether the coastal gravels were retreatal phenomena, connected with some late stage of the ice sheet's history, also what effect would be produced by the retreat northward of the *névé* line, whether the discontinuous gravels were due to the gradual rise of the sea, etc. The result has been to relegate all the suggested agencies to a subordinate position with respect to the two causes above named—a probable small acceleration of ice flow near the coast and the limited enlargement of the subglacial tunnels over the area whose basal ice was submerged in the sea.

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